62 Alternative Energy I: Control Software Needs of Renewable Energy Processes

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INTRODUCTION

In this chapter, we will describe some of the software packages that need to be developed for controlling and optimizing the new renewable energy processes, primarily in domestic applications. Traditional controls evolved from using single control loops. Renewable energy control is a step beyond that. Traditional industrial control concentrated on keeping flows, temperatures, pressures, etc., at their desired values, so these had only an indirect influence on efficiency, productivity, or profitability of the controlled unit operation. In contrast, the main goal of renewable energy control will be to optimize efficiency and profitability, while treating the operating conditions (temperature, pressure, etc.) only as limits of the operating envelope.

Traditional industrial control utilized multivariable control only in a few simple cases (such as ratio, cascade, feed forward, etc.) while renewable energy control will always be working with multivariable control. In addition, while traditional industrial controls often separated the different states of control for start-up, normal, emergency, and shut-down phases of operation, renewable energy controls will integrate these and will automatically reconfigure themselves as they respond to market conditions, energy, and raw material costs, and profitability related changes.

In order to correctly design a control system (any control system), it is essential to fully understand the "personality" of that process, both in terms of its operations and also in terms of its gains and dynamic characteristics (time constants, dead times, interactions, etc.). Therefore, before giving a few specific examples of the software packages needed to automate fully such renewable energy processes, in this chapter, first solar energy processes will be described, then optimization controls for the "energy-free" homes, and the "reversible fuel cells," will be discussed in detail.

RENEWABLE ENERGY PROCESSES

During the industrial and post-industrial period (from the eighteenth century to the end of the twenty-first), we have depended on exhaustible energy resources (fossil fuels, nuclear energy, etc.), while by the beginning of the twenty-second century, our energy sources will be inexhaustible ones. In Figure 62.1, the present energy consumption trend (based on NASA data) is illustrated. This trend, up to 2009 (lower solid line) represents the actual global consumption of the exhaustible fossil energy sources used in units of quads, ($Q = 10^{15}$ BTU). After 2009, the fossil fuel consumption trend (dotted line) shows, how our fossil energy supplies will start to get exhausted. The upper solid line represents the total global energy consumption, which includes all fossil, nuclear, and hydraulic energy sources.

The consumption rate of fossil fuels has already exceeded their rate of discovery. In spite of that, we are still directing our economic resources towards the building of new nuclear and fossil plants and on replacing our ageing refineries. This is happening in spite of both nuclear and fossil fuels being exhaustible and while both are getting more and more expensive. Canada is destroying her pristine environment by the dirty thermal process of recovering oil from sand, and the United States is risking other Exxon Valdez and BP accidents by deep sea drilling, and is risking nuclear meltdowns by continuing to operate some 104 nuclear plants.

Biological Life Cycle

It is also important to understand the biological life cycle on Earth (fueled by solar energy), which is based on the balance and interdependence of animal and plant life on the planet.

Photosynthesis takes up half of this cycle. In this half, the vegetation absorbs carbon dioxide and using solar energy splits water into oxygen and hydrogen (released into the atmosphere), which—using a catalyst named chlorophyll—combines with carbon from the atmosphere to produce food for animals and humans (photosynthesis $= H_2O +$ Sun Energy $+ 6CO_2 = C_6H_{12}O_6 + 6O_2$). The other half of the biological life cycle is respiration, in which animals and humans inhale the oxygen generated by plants and obtain their muscle energy by digesting (burning) the glucose, cellulose, etc., produced by plants, while exhaling carbon dioxide (respiration $= C_6H_{12}O_6 + 6O_2 = 6CO_2 + 6H_2O +$ energy).

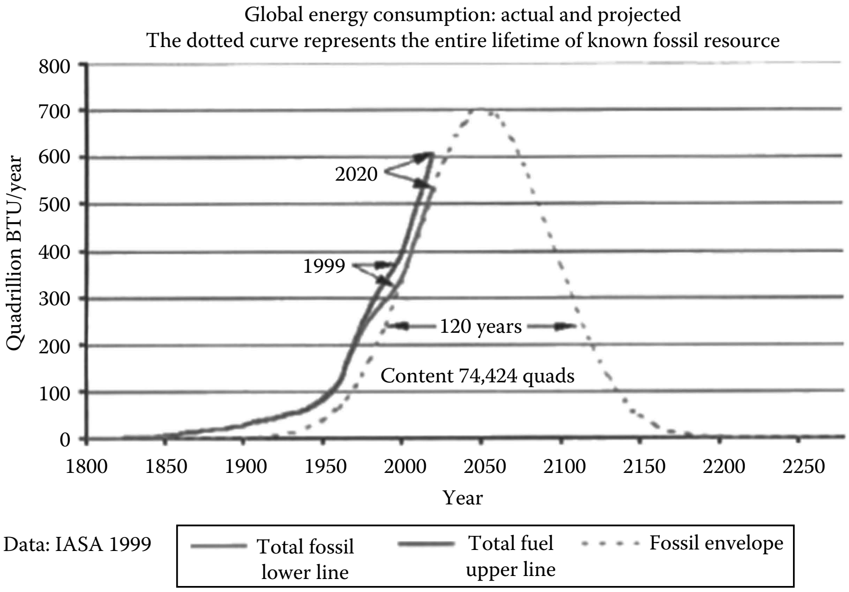


FIG. 62.1
Global energy consumption up to 1999 and projected fossil fuel availability in the future (dotted line).

When the half cycles of photosynthesis and respiration are in balance, the concentration of atmospheric CO_2 is constant. This concentration was 280 ppm for 500,000 years. Today the CO_2 concentration of the atmosphere is 360 ppm. It has been projected that by 2050 it will be over 500 ppm. This shows that plant and animal life on the planet is no longer in balance. Planting trees cannot correct this. In order to absorb the excess carbon dioxide generated by the burning of fossil fuels, we would need to plant forests on an area equaling the surface of another Earth.

The goal of renewable energy processes is to reestablish the balance of the photosynthesis and respiration processes. The solar-hydrogen processes can supplement the photosynthesis part (the role of plant life), but without the use of carbon.

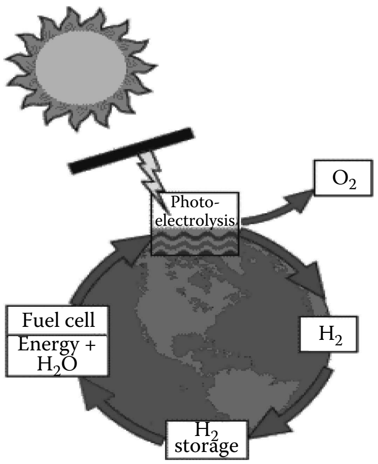


FIG. 62.2
Energy cycle without releasing carbon.

In this chapter, I will describe the software needed to control the solar–hydrogen processes (Figure 62.2) that form a cycle by substituting photosynthesis with photo-electrolysis (H_2O + Sun energy = Stored H_2 + Released O_2) and respiration with fuel cell (H_2 + O = Electric energy + H_2O) processes. This way, the increasing energy consumption of humankind can be met without releasing any carbon into the atmosphere and without the use of exhaustible energy resources, such as fossil or uranium.

Following this general introduction, I will describe the control software needs of three solar-hydrogen processes, which can fully automate the operation of the "energy-free homes," the "reversible fuel cells," and the "solar–hydrogen power plants" of the future.

ENERGY-FREE HOMES

The yearly solar energy received on each square meter of the Sahara is approximately 3000 kWh. Approximately 2500 kWh/m^2/year is the "insolation" in southern California and 1250 kWh/m^2/year in New York City or Connecticut (where I live). I will use my house as an example. I will first describe the method of calculating the costs and payback periods of an energy-free home installation and later, I will describe the design and optimization of such a system.

If our roof (450 m^2) was covered by 10% efficient photovoltaic (PV) solar collector shingles (Figure 62.3)—assuming that my wife allowed me to cut down the trees around our home, which she does not—these solar collectors would generate about 54,000 kWh/year. Our yearly electricity consumption, including that of the pool pump is 15,000 kWh/year, for which we pay slightly less than about $3000. Our

FIG. 62.3
Solar shingles can replace regular ones or they can also be added on top of existing ones.

yearly oil and propane consumption is equivalent to 864 gallons of oil, having an energy content of about 32,000 kWh.

Today, in our area, energy in the form of oil costs about half as much as it does in the form of electricity, because our oil taxes are rather low (elsewhere in the world, it is about twice as much). Therefore, the yearly total of our energy use (expressed in "kWh" units) is 47,000 kWh. This quantity being 7,000 kWh/year less than the amount of solar energy we can collect, this excess energy can be used to recharge a plug-in hybrid or electric car.

The installed cost of the solar shingles is about $500/m^2$ or about $225,000 to cover the roof. In Connecticut, the government subsidy is 40%, lowering the total investment to $135,000 (without considering the added advantage of having new shingles on the roof). The local power company provides the bidirectional electric meter needed to connect our electricity generation to the grid, free of charge.

The total value of 54,000 kWh/year of electricity, if purchased in the form of electricity at $0.2/kWh, is $10,800. If some of it is purchased in the form of fossil fuel, it is even less, but that cost is also rising. Therefore, if we base the calculation on the present cost of electricity, the payback period is 14.5 years. Naturally, if electricity costs rise or if collector costs drop and efficiencies increase, the payback period will be shorter. For example, the cost effectiveness will improve if we deduct from the total investment the value of covering the roof with new shingles, or if the location of our home were in Nevada instead of Connecticut, the payback period would be further reduced.

Next, I will discuss the use of renewable energy in private homes, starting with the simplest designs and gradually advancing to the more sophisticated ones.

Solar Hot Water Systems

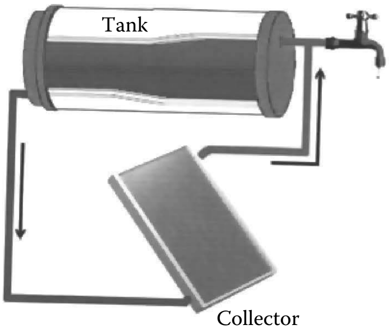
Direct thermal collectors are more efficient than indirect photovoltaic ones. The left side of Figure 62.4 illustrates the simplest ("passive") solar hot water collector. Here, the hot water rises into the collector tank. When the home consumes that hot water, fresh cold water replaces it. This system has no temperature controls and therefore it can overheat, requiring the use of a thermal expansion relief valve to protect the system from over pressure. The right side of Figure 62.4 shows the roof of a home, provided with both this direct hot water generator (left) and the photovoltaic (PV) solar collectors (right), to meet the electricity needs of the home.

Figure 62.5 illustrates the design of a "direct" solar hot water collector system controlled by a differential temperature switch (ΔTS). When the discharge temperature from the solar collector is high enough for the home, the circulating pump starts. When all the water in the hot water tank reaches the required temperature, the circulating pump stops. Naturally, if the solar hot water temperature is below the required temperature, the circulating pump also stops.

Figure 62.6 shows the operation of an "indirect" solar hot water collector system. This is similar to the "direct" system, except that it has two circulating loops and a heat exchanger to transfer the heat from the antifreeze fluid, circulating in one, into the water, circulating in the other. This configuration also makes the system suitable for winter operation. This system therefore is safer and more convenient than the direct one, but is also less efficient and more expensive.

Photovoltaic Systems

The photovoltaic solar cells generate DC electricity around 12–17 V. This electric power can directly charge batteries or



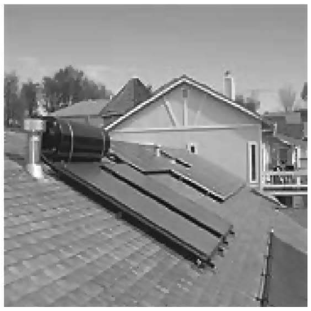


FIG. 62.4
The operation and installation of a solar hot water collector.

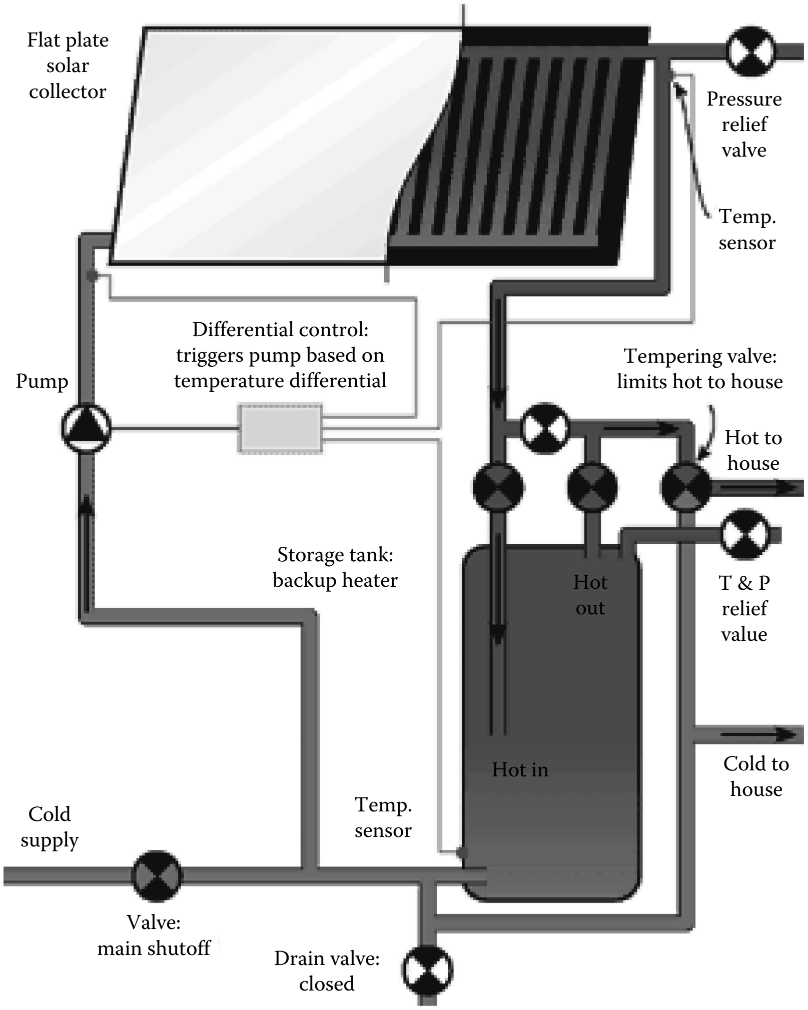

Flat plate solar collector
Pressure relief valve
Temp. sensor
Differential control: triggers pump based on temperature differential
Pump
Tempering valve: limits hot to house
Hot to house
Storage tank: backup heater
Hot out
T & P relief value
Hot in
Cold to house
Cold supply
Temp. sensor
Valve: main shutoff
Drain valve: closed

FIG. 62.5
Automatically controlled solar hot water collector system. (Courtesy of Arizona Solar Center, Scottsdale, AZ—http://www.azsolarcenter.org/tech-science/solar-for-consumers/solar-hot-water/solar-hot-water-a-primer.html)

operate electrolyzers. If the solar electricity is to meet the AC electricity needs of the home, the excess energy sent to the grid has to be converted into alternating current at higher voltages. In some installations, the generated electricity is consumed both in DC and AC forms and therefore combination systems are used. The following sections will discuss the software requirements for controlling and optimizing each of these systems.

PV Collectors and Their Control

Figure 62.7 describes the main components of a grid-connected photovoltaic solar collector system, and Figure 62.8 describes its wiring diagram, including an AC service entrance, AC and DC disconnect switches, inverter, wireless display, and two electric meters. One of the meters is tracking the total solar electricity production while the other is a bidirectional one, which is tracking the electricity flow to and from the grid and totalizes the net use or production of the household.

Inverters convert the direct current produced by the PV cells into alternating current. A simple electronic inverter is similar in function to the converters used in variable speed drives. In order to provide a grid connected inverter, it must maintain the same frequency as the incoming grid.

The control system must be able to detect the loss of the grid and respond to that by isolating itself from the grid or by tripping offline. The usual means of detecting a grid disconnect (or "island") condition is to have the output frequency periodically drift up or (more usually) down, because if the grid is in operation, the phase shift will be readily detectable. This way, at 2 or 3 Hz away from the nominal grid frequency, the inverter will trip to the "island" mode and either shut down (pending return of the main power supply) or disconnect itself from the grid.

An alternative method of detecting grid failure is to detect voltage deviation (either high or low) and set the inverter to trip, if the voltage deviation moves outside the range of +10% to −6% deviation band relative to the nominal

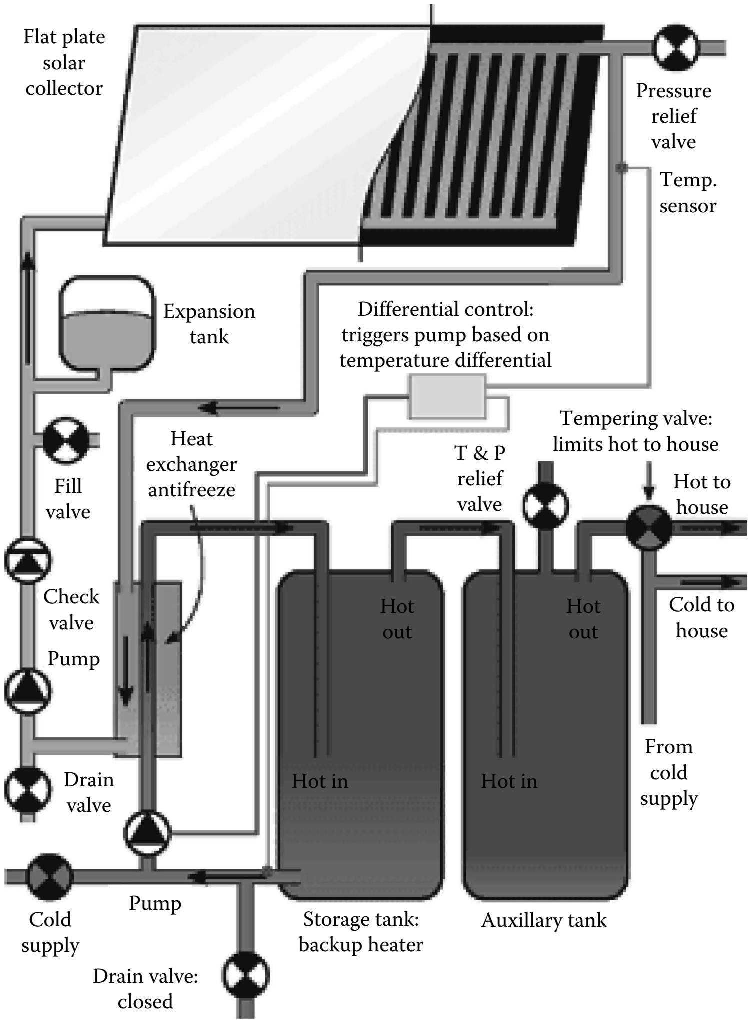


FIG. 62.6

Indirect automatically controlled solar hot water system. (Courtesy of Arizona Solar Center, Scottsdale, AZ—http://www.azsolarcenter.org/tech-science/solar-for-consumers/solar-hot-water/solar-hot-water-a-primer.html)

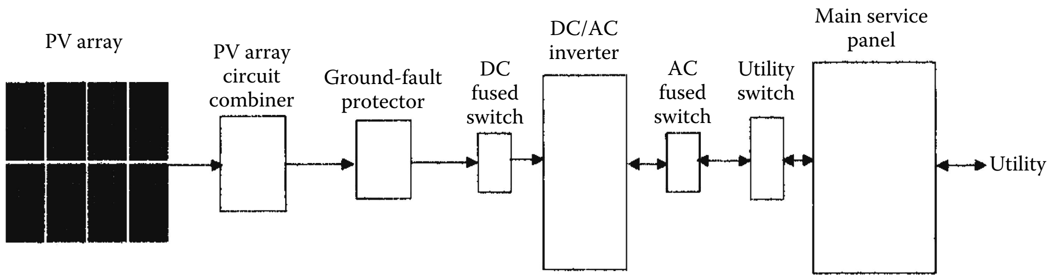


FIG. 62.7

The main components of a grid connected PV system.

supply values. The purpose of doing this is to protect the linesmen—from possible back feeds from generation systems—who might not be aware of this condition, when isolating the main supply. This system must detect a grid link failure within 2 min.

Grid connected inverters can either drive into the grid as a power supply or can supply part of a load. The third option is to drive the main's current draw to zero, which requires a more delicate balance. The choice among these options depends upon the specifics of the local electricity supply and

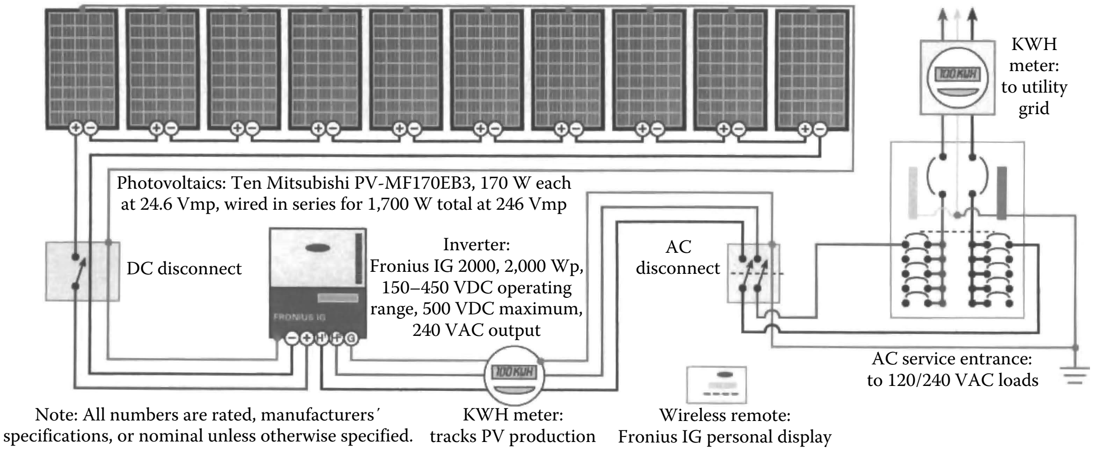

KWH
meter:
to utility
grid
Photovoltaics: Ten Mitsubishi PV-MF170EB3, 170 W each
at 24.6 Vmp, wired in series for 1,700 W total at 246 Vmp
DC disconnect
Inverter:
Fronius IG 2000, 2,000 Wp,
150–450 VDC operating
range, 500 VDC maximum,
240 VAC output
AC
disconnect
100 KWH
AC service entrance:
to 120/240 VAC loads
Note: All numbers are rated, manufacturers′
specifications, or nominal unless otherwise specified.
KWH meter:
tracks PV production
Wireless remote:
Fronius IG personal display

FIG. 62.8

Grid connected PV collector system. The system sends the excess electricity to the grid and the bidirectional kWh meter is running "backwards." (Copyright 2007 by home power, Inc. www.homepower.com)

upon the receptiveness of the supply authority to accept electric power from generators owned by others.

The excess solar energy can go to the grid or into local storage. The optimization software will consider the following factors in making this decision:

1. Is there excess solar electricity available? If there is, is there room in local storage to receive more electricity? Under the above conditions:
2. Is it more economical to send the excess to the grid (during peak periods, when/if payment by utility can be higher) or to storage (during low payment periods)?
3. If there is no excess solar electricity available and the household needs more from the grid, is excess stored electricity available as an alternate source (is storage full or above minimum reserve needed)? If this is the case:
4. Should the needed electricity be obtained from storage (during periods, when/if charge by utility is higher) or from the grid (during low payment periods)?

STORING SOLAR ENERGY

The safe, efficient, and inexpensive storage and transportation of solar energy is the key to convert from today's exhaustible energy sources (fossil and nuclear) to inexhaustible, clean, and free renewable energy supplies. Therefore, I will discuss the control software needs of these new processes, but before discussing their control and optimization, I will describe the processes themselves.

Solar energy can be stored in the forms of electric, chemical, or heat energy. Storage in the form of electricity can use the grid or batteries; storage in the chemical form can utilize several reactions, one of which is generating hydrogen fuel from water by electrolysis and storing it as heat energy in hot water, hot oil, or molten salt. I will start this discussion by describing the state of the art of storing solar electricity in batteries.

Storing Solar-Generated Electricity in Batteries

Solar electricity can be stored in separate battery blocks (Figure 62.9) or in the batteries of electric or regular cars. The stored energy can provide nighttime electricity for the home, can charge the car batteries, and can be sent to the grid. The time when excess solar electricity is available usually coincides with the time when the air conditioning loads are high and, therefore, this electricity is helpful to the power company as it reduces the peak load on the grid. One of the tasks of the optimization software is to direct the excess electricity to meet all needs while maximizing profitability, considering the differences in the values of electricity at the various destinations.

The performance of batteries has improved during the last decades. The energy density (Wh/kg) of lead-acid batteries used to be about 50 Wh/kg and their life expectancy was between 2 and 5 years. For example, a 6 V, 210 Ah (ampere-hour) golf cart battery stored about 1.26 kWh (Volts × Ah = k Wh, 6 × 210 = 1.26 k Wh) and weighed about 30 kg. Trailers or motor homes usually use only a single 12 V house battery. These batteries often use Gel Cell or Absorbed Glass Mat (AGM) designs instead of Wet Cells, because these are suited for harsher environments, require less maintenance, and provide the greatest reserve capacity (Ah = ampere hour).

The individual cells of lead-acid house batteries generate about 0.8 V and two 12 V batteries can power 4 kW inverters. Table 62.1 gives the size codes commonly used for batteries.

Lithium ion batteries improved on the energy density of batteries to about 70 Wh/kg. The energy density in the lithium-ion batteries that are used in electric cars (Figure 62.10) is over 200 Wh/kg, their power density is over 300 W/kg, and their volumetric energy density is up to over 500/Whl. The

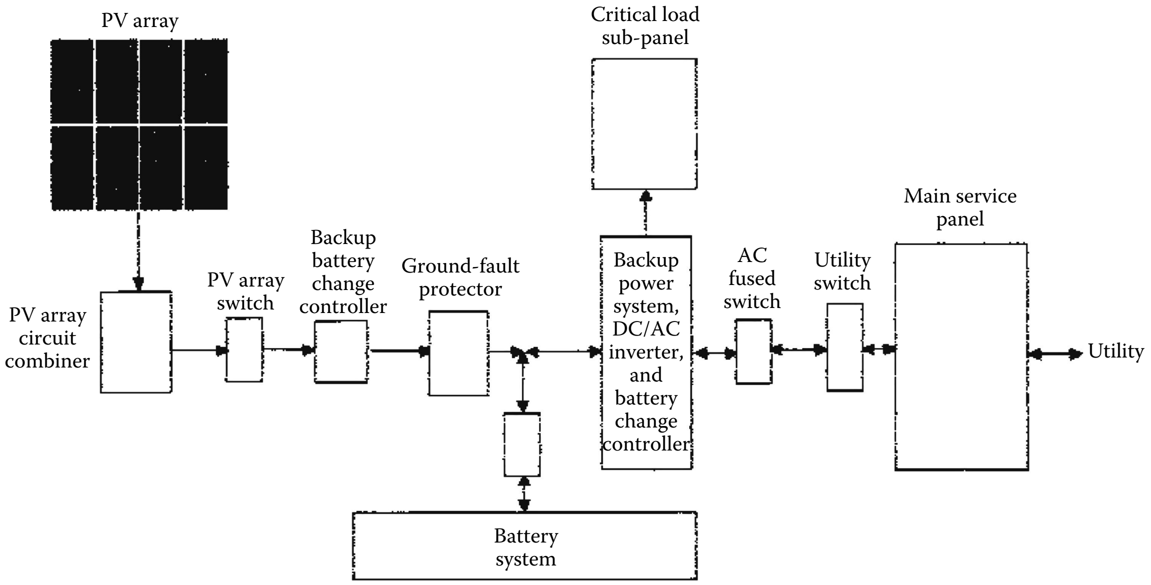


FIG. 62.9
The main components of a grid connected home that is also provided with battery backup.

TABLE 62.1
Common Battery Size Codes (Ratings Are Approximate)

U1	34–40 Amph	12 V
Group 24	70–85 Amph	12 V
Group 27	85–105 Amph	12 V
Group 31	95–125 Amph	12 V
4-D	180–215 Amph	12 V
8-D	225–255 Amph	12 V
L-16, L16HC, etc.	340–415 Amph	6 V

lithium-ion battery life has not improved much (2–5 years), but the newer NiMH batteries do last the life of the car and their charge-to-energy efficiency has reached nearly 90%.

Both the driving range and economics of batteries are improving with time. An electric car—depending on its size—requires between 0.25 and 0.5 kWh electric energy per mile of driving and the cost of today's batteries is about $500 per kWh. Therefore, the purchase price of a battery block, large enough for 100 miles of driving between refills or replacements is $12,500–$25.00. It is an open question, if the electric car "filling stations" of the future will just replace the empty battery blocks with full ones, which would take a couple of minutes, or will it be operating on a "plug in recharge" basis, which takes longer. In any case, today the high battery costs still limit the use of all-electric cars.

On the other hand, the battery cost component in today's hybrid cars is much lower. For example, the battery block in a Prius hybrid car costs about $3000. It is projected that by 2012 the battery costs will drop to less than half to about $200/kWh and will continue to drop further as mass production starts.

As to operating costs, the economics already favor the electric cars over the Internal Combustion (IC) engine. At a cost of $3/gallon and at an average fleet mileage of 30 mpg, the cost of driving an IC engine car is about $0.1 per mile. As the energy content of a gallon of gasoline is about 10 kWh, at a unit cost of $0.15/kWh and with an electricity consumption of 0.3 kWh per mile, the cost of driving an electric car is about half of the IC type ($0.15 \times 0.3 = \$0.045$). Naturally, as the cost of gasoline rises and as the cost of batteries drop, the economic advantage of driving electric cars will further increase.

Nissan leaf went on sale in 2011 for around $21K

Today, India's Revai is the world's most popular electric car

FIG. 62.10
Examples of electric cars.

The race between Fuel Cells (FC) and batteries is not yet over. Today, economics favor the batteries, but the long-range outcome is undecided. As electric cars take over as the means of transportation, the availability and cost of the materials used will become an important factor. In the case of the fuel cells, the outcome will depend on the cost and availability of the catalysts and for the batteries, it will depend on the cost and availability of lithium, nickel, etc. As discussed later, in the paragraph dealing with Reversible Fuel Cells (RFC), extensive research efforts are in progress to develop inexpensive catalysts and to increase efficiency by exploiting nanotechnology.

Solar Battery Charge Controllers

The larger the solar electricity collection system, the more sophisticated the battery charge controllers are. They usually provide digital interfaces and interactive displays, which can be integral with the controller or can be wireless connections to the user's PC. In either case, the man-machine interface allows the home's owner to check at any time the charging voltage and amount of electrical energy stored and to modify the limit settings for each mode of operation. Some suppliers of charge controllers are Xantrex Technology, Morningstar, Outback Power, Blue Sky Energy, and Steca.

For very small systems, a 30 A controller with an LCD display costs about $50, while the solar inverter needed can be as inexpensive as $10. Even these least expensive voltage controllers are usually provided with features such as

1. Overload protection
2. Short-circuit protection
3. Reverse discharge protection
4. Reverse polarity connection protection
5. Thunder protection
6. Low voltage protection
7. Overcharge protection
8. Battery stop-and-charge voltage HVD (High Voltage Differential) features
9. Charge-and-low voltage LCD (Liquid Crystal Display).
10. Display the capability of the battery SOC (State of charge)
11. Loads and comeback features
12. Temperature compensation
13. Store, calculate, and display of the charged Ah (ampere-hour) on the LCD screen
14. Store, calculate. and display the discharged A (amperes) on the LCD screen
15. Temperature range: from −25°C to +55°C

CONTROL SOFTWARE FOR PV WITH STORAGE

The optimization software needed for PV systems, having both storage and grid connections, have to provide the following functions:

1. Provide total automation, including record keeping
2. Provide the means for automatically reconfiguring the system to maximize profitability
3. Provide safety and report need for maintenance through self-diagnostics

In developing the software package, the primary goal must be user's simplicity so that its operation will require no more understanding by the homeowner than what today's thermostats require. This requires total automation, so that the system will safely operate on its own, without the need for the homeowner to take any action at all. On the other hand, it must allow the homeowner to update or manually modify any information or target such as the price of electricity during normal, night, or peak periods, the amount of electricity stored in the various batteries, and the minimum limit for the amount of electricity that must remain in storage for driving.

Grid-Connected PV Systems Having Battery Storage

Figure 62.11 shows the wiring of a grid connected PV solar collector system with battery storage. These systems can receive electricity from three sources:

1. The solar collectors
2. The grid
3. Battery storage

These systems can direct the generated solar electricity to three (3) destinations:

1. The home
2. The grid
3. Battery storage

The goal of the control system is to achieve economic optimization by sending the excess electricity to the destination that is paying the most for it while obtaining supplemental electricity from the least expensive source. This usually means that the excess electricity from the collectors can be sent to battery storage or to the grid during "peak periods", if during these periods, the utility pays peak unit price for it. Similarly, one can look at the price of electricity from the grid and recharge the partially full batteries from the grid when the electricity is inexpensive ("night" time electricity) or use the electricity stored to meet the demand of the home.

In order to implement the above strategies, it is necessary to know the minimum amount of electricity that should remain in the car batteries (B_{min}) to meet the driving needs of the household and what is their total storage capacity ($B_{cap} = 100\%$). In the automatic mode, the B_{min} setting can be set differently for weekdays and weekends. The homeowner can reset all of these settings.

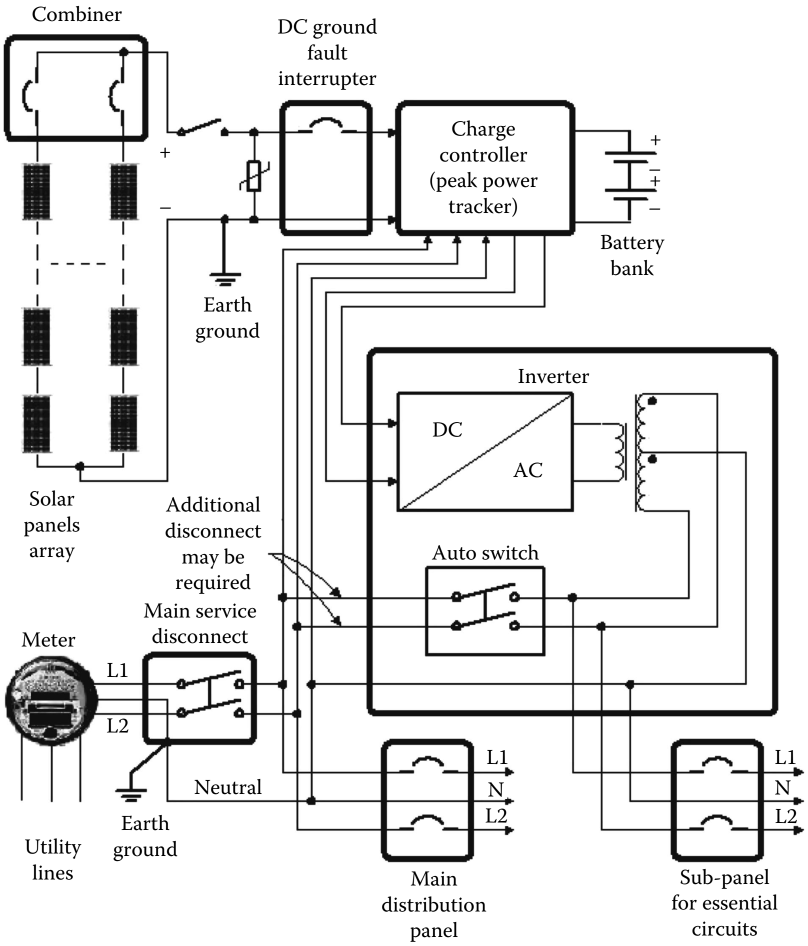


FIG. 62.11
The wiring of a grid connected home that is also provided with battery storage. (See solar.smps.us/grid-tie-backup.html for details.)

In the automatic mode, the optimization software answers the following two questions:

1. Should excess electricity go to storage (batteries) or be sent to the grid?
2. Should the electricity needed by the home come from storage or be obtained from the grid?

The software package should also support status displays. These displays can be part of the controller and/or displayed on the home's PC or TV using wireless connections. The information displayed might include

1. Amount of electricity stored in the batteries ($B_s = \% B_{cap}$)
2. Electricity reserve needed ($B_{min} = \% B_{cap}$)
3. Price charged by utility for 1kWh from the grid ($)
4. Price paid by utility for 1kWh sent to the grid ($)
5. Excess solar electricity being sent to storage (kWh)
6. Excess solar electricity being sent to grid (kWh)
7. Percentage of household's needs met by solar electricity, rest from storage
8. Percentage of household's needs met by solar electricity, rest from grid

PV Systems Having No Grid Connection

In locations where no electric grid exists, it is unreliable or if the electric company does not allow the use of two-directional electric meters, one has to use self-supporting solar packages. Therefore, when there is no grid connection and the storage capacity of the batteries is not sufficient to store all the energy needed, one option is to use an electric generator that supplements the battery backup. The control and optimization strategy for such combination is the same as was described in connection with Figures 62.9 and 62.11. The only difference is that the excess electricity is stored in the batteries. When the home needs electricity, it uses this storage until it is exhausted. The generator is to start at that point.

The use of an electric generator as a backup is only a half way measure, because that configuration still depends on a supply of fossil fuel and besides emitting carbon dioxide, it is not completely self-sufficient. In the next paragraph, I will describe a design which has zero emission and is completely self sufficient, if the yearly energy requirement of the home (including the requirements of the electric cars) is less than the insolation in the area. In the earlier paragraph titled "The Energy-Free Home", the required calculation has already been described.

In the next section, I will describe a completely self-sufficient solar package that requires no grid or generator backup and has zero emission.

SOLAR–HYDROGEN SYSTEM

In a solar–hydrogen system, the solar energy is stored in hydrogen, which is used when the Sun is not out thereby making the solar energy continuously available. To convert the excess solar energy into hydrogen, an electrolyzer is used, and to convert the hydrogen back into electricity a fuel cell is used.

It takes the same amount of energy to split water into hydrogen and oxygen as the energy obtained when oxidizing hydrogen back into water. The only difference between the two operations is that electrolysis increases the entropy while the fuel cell reaction decreases it. Therefore, in the electrolysis mode, the environment contributes 48.7 kJ/mol of thermal energy. Inversely, in the fuel cell mode, part of the energy generated by burning hydrogen produces only heat.

Therefore, the electrolysis mode of operation requires heating and the fuel cell mode needs cooling (or heat recovery). The hydrogen is collected at about 3 bar (45 psig) of pressure and is either liquefied or is compressed to some high pressure for storage. When solar electricity is insufficient, the oxidation of one mol of hydrogen will generate 237.1 kJ/mol of electrical energy plus 48.7 kJ/mol of thermal energy. The home can be heated or this waste heat can generate hot water.

REVERSIBLE FUEL CELL

When the Sun is out, the reversible fuel cell (RFC) takes the excess electricity that is being generated by the solar collectors and acts like an electrolyzer using this excess electricity to split water into hydrogen and oxygen and to store the H_2 while releasing O_2 into the air. When the Sun is not out, the

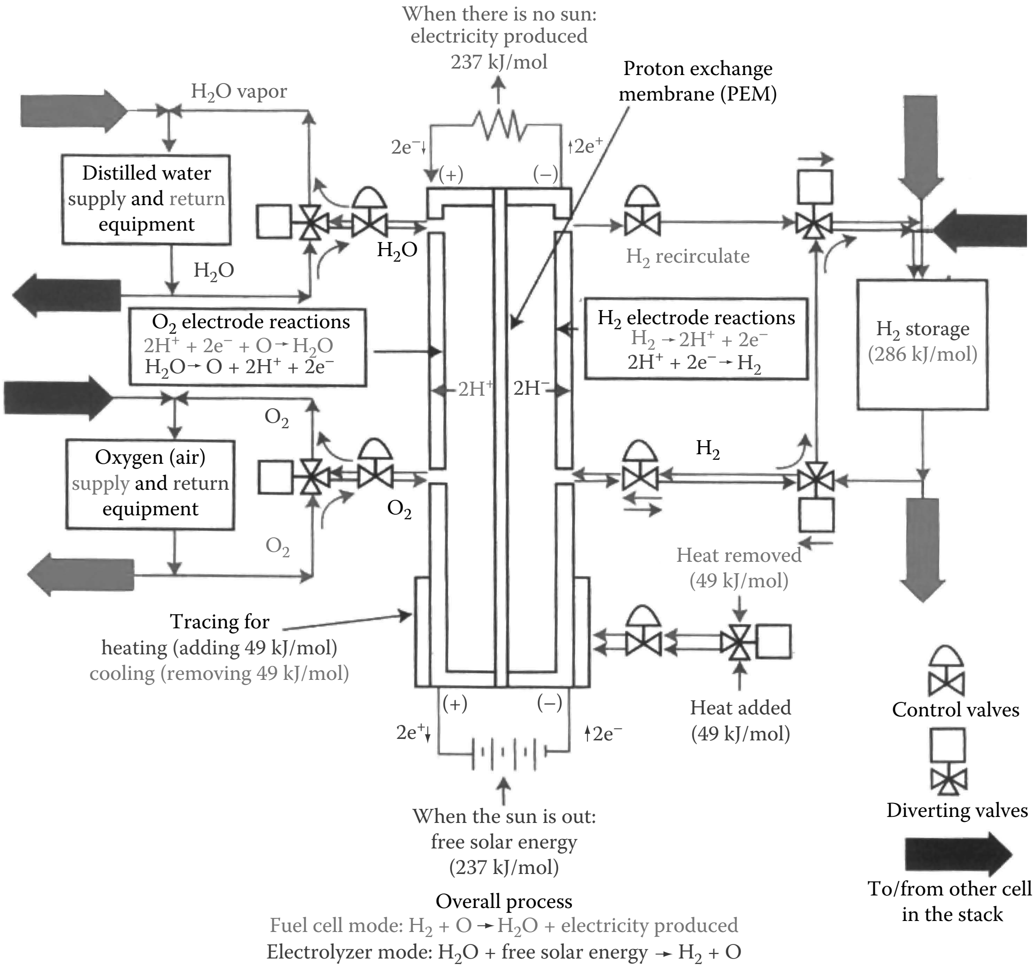


FIG. 62.12
This figure illustrates one cell of the Reversible Fuel Cell (RFC) block using the basic Proton Electrolyte Membrane (PEM) design. The heavy lines show the RFC operation in the fuel cell mode and light lines describe the RFC operation in the electrolyzer mode.

flow direction in the RFC is reversed and its "personality" changes into that of a fuel cell using hydrogen to generate electricity. This way, solar energy is continuously available, even when the Sun is not shining. These dual-state fuel cells are expected to be much lighter than the combined weights of separate electrolyzers and fuel cells. Figure 62.12 describes the reversible fuel cell.

The RFC sizes will be in the range of 1–10 kWh and their control will be as simple as today's thermostats are. If the home's owner puts the controls into the automatic mode, the logic inside would automatically consider solar availability, electricity demand, electricity storage availability (in electric car or other batteries), H_2 storage availability, electricity cost from the grid, and if cost changes from day to night.

Controlling the RFC

The control software of the RFC will integrate four software packages. One will control the system in the electrolyzer mode, when the Sun is shining and the collectors are generating more electricity than needed for the home. The second sub-package will control the RFC in the fuel cell mode, when the solar electricity generated is zero or is insufficient to meet the needs of the household. In the fuel cell mode, the stored hydrogen provides the electricity needed to supplement the needs of the household. The third sub-package controls the sequence of the conversion steps between the electrolyzer and the fuel cell modes of operation.

The fourth sub-package serves economic optimization of the overall operation by considering if the amount of stored energy should be increased or if excess energy is available from storage (either in the batteries or in the form of hydrogen), and the value of electricity to and from the grid.

The role of process control is critical in operating RFCs. The reader can visualize the complexity of the control challenge by comparing the control challenge of a 400-cell RFC stack to controlling 400 pumps operating in parallel. This complexity is even greater because the switching of the RFC from one mode of operation to the other is as challenging as shooting down one process and starting up another. Fortunately, the switchover does not need to occur quickly, but once the processes are running, they are fast. For example, it takes only a couple of seconds between starting to send hydrogen into the fuel cell and beginning to generate electricity and the speed of electrolyzer response is similar.

In addition to operating the grid connection (Figure 62.8) and controlling the rates of hydrogen or electricity generation, a massive quantity of measurements and control circuits are needed not only to sequence the switching between modes of operation, but also to switch between the heating and cooling modes of control as the operating modes of the RFC are reversed. The material and heat balance in both of these modes require high rangeability and accurate temperature controls. It is also necessary to control the pressures of the oxygen and hydrogen streams that are entering the RFC in the fuel cell mode or leaving the RFC in the electrolyzer mode. The pressure difference across the fuel cell diaphragms must be nearly zero in order not to damage them.

The load controls in both modes of operation require fast and accurate flow controls. In the fuel cell mode, the hydrogen fuel, while in the electrolyzer mode the water flow needs to be controlled. In the FC mode the generated distilled water and in the electrolyzer mode the generated oxygen has to be directed to its destination.

All the sensors and control chips will have to be miniature, high accuracy, and inexpensive, just like the ones used in the automobile industry (a single modern car has 500 sensors). Therefore, process control will play a leading role in the competition among RFC manufacturers. The RFCs will have to be small, light, and inexpensive and will have high accuracy and stable controls.